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Probabilistic Assessment of Smart Composite Structures

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NASA

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SUMMARY

A composite wing with spars and bulkheads is used to demonstrate the effectiveness of probabilistic assessment of smart composite structures to control uncertainties in distortions and stresses. Results show that a smart composite wing can be controlled to minimize distortions and to have specified stress levels in the presence of defects. Structural responses such as changes in angle of attack, vertical displacements, and stress in the control and controlled plies are probabilistically assessed to quantify their respective uncertainties. Sensitivity factors are evaluated to identify those parameters that have the greatest influence on a specific structural response. Results show that smart composite structures can be configured to control both distortions and ply stresses to satisfy specified design requirements.

INTRODUCTION

Aircraft and aerospace structures are complex assemblages of structural components that operate under severe and uncertain service environments. These types of structures require durability, high reliability, light weight, high performance, and affordable cost. To meet these requirements, composite materials are being considered as attractive potential candidates. Composite materials possess outstanding mechanical properties with excellent fatigue strength and corrosion resistance. Their mechanical properties depend on a wide variety of variables such as the constituent material properties and laminate characteristics (fiber and void volume ratios, ply orientation, and ply thickness). These variables are random and can only be described by a range of values. The current design practice to deal with these uncertainties is to enforce a knockdown factor for each unknown, which minimizes the advantages of using composite materials for structural design. To use composite materials adequately, a probabilistic assessment of composite structures is needed to quantify their structural behavior and variability.

Recent developments in the application of smart structures concepts, using sensor/control materials, show the potential to enhance structural performance as well as durability and reliability (refs. 1 and 2). Briefly, sensor/control devices consist of the following: (1) an electronically polarized material, (2) an electric field parallel to the direction of polarization, and (3) expansion and contraction effects of the polarized material. When control voltages are applied in the direction of polarization during normal operation, the sensor/control material expands in the same direction so that the structural behavior is altered by a desired amount; thus, its reliability is enhanced. These control voltages can be readily integrated into a smart composite structure by using combinations of intraply and interply hybrid composites. It is then possible to ensure that smart composite structures will operate in the design-specified range. At the NASA Lewis Research Center, the intraply

hybrid mechanics for composites is embedded in the computer code ICAN (Integrated Composite Analyser) (ref. 3) for integrated composite analysis.

The uncertainties inherent in composite and smart structure parameters can be evaluated by using probabilistic composite structural analysis methods as described in the following sections.

SYMBOLS

E_{f11}	fiber modulus in longitudinal direction, Mpsi
E_{f22}	fiber modulus in transverse direction, Mpsi
E_m	matrix elastic modulus, Mpsi
G_{f12}	in-plane fiber shear modulus, Mpsi
G_{f23}	out-of-plane fiber shear modulus, Mpsi
G_m	matrix shear modulus, Mpsi
fvr	fiber volume ratio
stdv	standard deviation
t_p	ply thickness, in.
vvr	void volume ratio
α	angle-of-attack redline
θ_p	ply misorientation, deg
v_{f12}	in-plane fiber Poisson's ratio
v_{f23}	out-of-plane fiber Poission's ratio
v_m	matrix Poisson's ratio

FUNDAMENTAL CONCEPTS

The smart structure concept, the intraply hybrid composite adaptation, and the IPACS (Integrated Probabilistic Assessment of Composite Structures) code are briefly described here for completeness.

Smart Structures

Figure 1 depicts a conceptual diagram of a smart composite wing system. The essential parts of a smart structure include (1) a structure, (2) strategically located sensors, (3) signal processors that process the signals

generated by the sensors, (4) dedicated computers with suitable software that continuously checks the structural response magnitude and compares it to predetermined critical (redline) values; these values then provide desired corrections to the controller, (5) a controller that signals the actuator to implement the desired corrections, and (6) actuators. The sequence for controlling the structure is as follows: (1) the sensors monitor the various critical structural responses that affect the safety of the structure; (2) the signals are transferred to a signal processor that filters and converts them to magnitudes that the dedicated computer can recognize; (3) the computer software compares those magnitudes to critical (redline) values; (4) the software informs the signal processor when the magnitudes are near the redline values; (5) the signal processor signals the controller to activate the actuators to take action to reduce the magnitudes; and (6) the actuators implement the signalled action. In short, the concept of smart structures is a closed-loop system as seen in figure 1.

Intraply Hybrid Composite Adaptation

The adaptation of the intraply hybrid composite concept (ref. 4) to smart composite structures is depicted schematically in figure 2. Figure 2(a) shows the intraply hybrid configuration and figure 2(b) shows its adaptation to smart composite structures.

Note from figure 2 that the intraply hybrid composite consists of plies that have strips of a regular (host) composite material and interspersed strips of material for sensor/control devices. Actuators, made of control materials such as piezoelectric ceramic or fiber, are used to control the behavior of the composite structure by expanding (positive-induced strain) or contracting (negative-induced strain) the sensor/control strips to achieve the requisite design and operational goals. However, the strains induced by the actuator are affected by uncertainties in several factors that can only be quantified probabilistically. These include the following:
(1) inaccurate measurements made by the sensors, (2) uncertainties in the electric field, (3) uncertain induced-strain–electric-field strength relationship, (4) uncertain material properties for the sensor/control materials, (5) uncertain electric field strength, and (6) improper location of the sensor/control materials. Because of these factors, the use of sensor/control devices increases the uncertainty in the already uncertain composite structural behavior. To properly quantify the benefits of the induced strain, a comprehensive probabilistic assessment is needed.

IPACS Computer Code

The IPACS computer code has evolved from extensive research activities at NASA Lewis to develop probabilistic structural analysis methods (ref. 5) and computational composite mechanics (ref. 3). The composite micromechanics, macromechanics, and laminate theory, including interply and intraply hybrids, are embodied in ICAN (ref. 3). A block diagram of IPACS is shown in figure 3.

IPACS consists of direct coupling of two stand-alone computer modules: PICAN (Probabilistic Integrated Composite Analyzer) and NESSUS (Numerical Evaluation of Stochastic Structures). PICAN is used to simulate probabilistic composite mechanics (ref. 6). NESSUS is used to simulate probabilistic structural analysis (ref. 7). Direct coupling of these two modules makes it possible to simulate the uncertainties in all inherent scales of the composites — from constituent materials (bottom, fig. 3) to a composite structure including its boundary and loading conditions as well as environmental effects (top, fig. 3).

The procedure for applying IPACS for the probabilistic assessment of smart composite structures is as follows: (1) the induced control strains are simulated using thermal strain computed from uncertain temperature (representing the electric field strength) and uncertain thermal expansion coefficients (representing the sensor/

control strain coefficients); these thermal strains are in addition to those from thermal loads; (2) the scatter in the primitive variables, which describe the composite, can be represented by well-known probabilistic distributions; (3) values from these distributions can be used in probabilistic composite mechanics to predict uncertainties in the composite behavior; and (4) the primitive variables are identified at micro- and macro-levels.

The primitive variables recognized by the computer code IPACS are (1) fiber and matrix properties at the constituent level, (2) fabrication parameters such as fiber volume ratio, void volume ratio, ply misorientation, and ply thickness, (3) uncertain loads, temperature and moisture, geometry, and boundary conditions at the structural level, and (4) uncertain electric field strength and strain coefficient for the sensor/control material strip. The assessment is based on assigning a probability distribution for each of the primitive variables. The uncertainties in the primitive variables are then propagated through the computational simulation, which consists of composite mechanics, structural mechanics, and probability methods.

The probabilistic assessment of smart composite structures starts with the identification of uncertain primitive variables at constituent and ply levels. These variables are then selectively perturbed several times to create a data base. The data base is used to establish the relationship between the desired structural response (or the desired material property) and the primitive variables. For every given perturbed primitive variable, micromechanics is applied to determine the corresponding perturbed mechanical properties at the ply and laminate level. Laminate theory is then used to determine the perturbed resultant force-moment–strain-curvature relationship. With this relationship at the laminate level, a finite element perturbation analysis is performed to determine the perturbed structural responses corresponding to the selectively perturbed primitive variables. This process is repeated until enough data are generated so that the appropriate relationships between structural responses and primitive variables can be estimated.

Given the probability distributions for the primitive variables and an estimated relationship between the structural response and the primitive variables, fast probability integration (FPI) (ref. 8) is used to generate the response uncertainty. For every discrete response value, a corresponding cumulative probability can be computed quickly by FPI. This process is repeated until the cumulative distribution function can be appropriately represented. The probabilistic material properties at ply and laminate levels are also computed in the same way as that for the structural responses. The output information from FPI for a given structural response includes its discrete cumulative density function values, the coefficients for a special type of probability distribution function, and the sensitivity factors of the primitive variables to the structural response.

DEMONSTRATION USING A SMART COMPOSITE WING

The probabilistic assessment of the smart composite structure concept as described previously is demonstrated by using it to analyze a smart composite wing. A comparable assessment for a composite plate is described in reference 9. The geometry of the composite wing and its internal structure are shown in figure 4(a). The wing is assumed to be loaded with nonuniform pressure, which varies parabolically from root to tip, as shown in figure 4(b).

The composite wing is assumed to be made from AS graphite-fiber/epoxy-matrix composite. The laminate configurations for skin, spars, and bulkheads are $[\pm45/0/90_2/0/\pm45]_s$, $[0_8]$, and $[0_8]$, respectively. Table I summarizes the constituent materials properties, their assumed probabilistic distribution, and the range of the scatter. Table II summarizes the corresponding fabrication variables used to make the composite wing and table III shows those for the sensor/control device. Reference 10 gives a more detailed description of the wing.

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PROBABILISTIC ASSESSMENT — WING WITHOUT HOLES

The critical structural responses in the performance of aircraft wings studied in this report are changes in the angle of attack and vertical displacements (fig. 1). Each is discussed here.

Uncertainties in Angle of Attack

The uncertainties in the angle of attack were evaluated as the range of the probable scatter from a zero reference position. Results for the probable scatter in the angle of attack at midspan are shown in figure 5(a) for a wing with and without controls. Corresponding results at the tip are shown in figure 5(b). Three important observations to note are (1) controls can be configured to change the angle of attack substantially: 0.5 percent in contrast to 1.0 percent induced strain; (2) the spread in the scatter increases as the magnitude of the control-induced action increases; and (3) the opening had no effect on the distribution in the angle of attack.

Uncertainties in Vertical Displacement

The scatter in the vertical displacement with and without two magnitudes of control strains are shown for the wing at midspan leading edge (fig. 6(a)) and at midspan trailing edge (fig. 6(b)). Note that substantial changes in vertical displacement can be induced. Figure 7 shows comparable results for the vertical displacement at the tip. The collective results (figs. 5 to 7) demonstrate that the intraply hybrid composite concept is an effective means to control displacements in smart composite structures.

PROBABILISTIC ASSESSMENT — WING WITH ACCESS OPENINGS

In the previous sections, smart composite wings for controlled displacements were described. In this section, the concept is extended to composite wings with two types of defects: small round holes and rectangular openings. The latter may be more representative of access ports for servicing and inspection.

Composite Wing Geometry

The composite wing is the same as that described previously in the section Demonstration Using a Smart Composite Wing. The location of the defects are near the root where the stresses are high (fig. 8).

Longitudinal Stress Uncertainties Range — Small Round Hole

The scatter of the ply longitudinal stress in the four different plies is shown in figure 9. The control strains are induced in the +45° ply. Several points are worth mentioning with respect to this figure: (1) the ply stresses are normalized with respect to the ply longitudinal stress to estimate changes in the stresses by changes in either the loads or in the control-induced strains; (2) the stresses in the control ply increase rapidly with increased induced strain. This is highly desirable since control plies, which are lightly loaded, can be selected; (3) the stresses in the critical (controlled) 0° ply decrease rapidly with induced control strain. This is another desirable feature since control-induced strains can reduce the stress in the controlled ply by specific magnitudes; (4) the stresses in other plies (-45° and 90° plies, for this case) also change rapidly by the stresses induced in the control ply; the magnitudes of the stresses need to be determined for the specific situation examined; (5) the scatter in the ply stresses increases with increased control strain, which, in many cases, causes overlapping; and

(6) although actual stress magnitudes are not shown here, they are only a small fraction (5 to 10 percent) of the 0° ply stresses in all other plies. Collectively, these results demonstrate that smart composite wings can be configured to control ply stress in stress concentration regions by a probabilistic approach.

Longitudinal Stress Uncertainties Range — Rectangular Opening

The probabilistic scatter of normalized ply longitudinal stresses is shown in figure 10. The control ply for this case is also the +45° ply. Note that the stresses without the opening (labeled "without hole") are also shown for comparison. As seen, the stress magnitudes in the controlled ply (0° ply) can be modified to approach those of the wing without access openings. The general behavior is comparable to corresponding plies with the small round hole as described in the previous section.

Normalized Ply Stresses

Figure 11 shows normalized ply, +45° stresses. The longitudinal stresses are the same as those shown in figure 10. The other two stresses (transverse and interlaminar shear) are normalized with respect to the longitudinal stress. This is done to demonstrate the relative magnitude of matrix-dominated stresses compared with cor-responding longitudinal stresses. Because the transverse stresses attain relatively high magnitudes, controls in adjacent plies may have to be actuated to reduce these magnitudes to acceptable levels.

Corresponding ply stresses in the -45° ply are shown in figure 12. These results show that the transverse stresses can be altered from tension to compression, which is an effective means to prevent matrix transply cracking. The intraply shear stresses are relatively high, are not sensitive to the control-induced strains, and will need to be controlled to avoid intraply shear fracture initiation.

The corresponding ply stresses for the controlled (0°) ply are shown in figure 13. The important observations in this figure are that the magnitudes of the transverse and intralaminar shear stresses are about 5 percent or less of the longitudinal stress, and more important, the transverse stresses are compressive. The significant conclusion is that the matrix-dominated ply stresses are relatively insignificant in the controlled plies of a smart composite structure with defects. The corresponding normalized stresses in the 90° ply are shown in figure 14. The transverse stresses are in compression whereas the shear stresses are of relatively small magnitude compared with the longitudinal stress.

Again the important conclusion is that the local ply stresses in smart composite structures with access openings can be probabilistically quantified and their magnitudes can be modified accordingly to prevent local fracture initiations in specified operating ranges.

Sensitivity Factors

Sensitivity factors for the wing with a rectangular opening (cutout) are an important feature of probabilistic assessment of smart composite structures. These factors provide quantifiable information on the design parameters to which the smart composite structural concept is most sensitive. Subsequently, these design parameters can be modified to obtain the best benefit with minimum alteration. The sensitivity factors for the control and controlled ply are discussed herein to illustrate their effectiveness.

The sensitivity factors for the longitudinal stress in the controlled (+45°) ply are shown in figure 15(a) for the four different cases investigated. Note that (1) the composite design parameters (longitudinal modulus, the

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fiber volume ratio, and the ply misorientation) dominate this stress without the controls in the cases of with and without hole; (2) the control design parameters (electric field and the sensor/control volume ratio) dominate in the cases with the controls; and (3) the dominance of control design parameters becomes more significant as the control-induced strain increases.

The sensitivity factors for the longitudinal stress in the controlled (0°) ply are shown in figure 15(b). For this case, the design parameters for skin laminate and wing inner structure dominate up to an induced strain of 0.5 percent. The control design parameters become relatively significant when the control-induced strain-approaches 1 percent. Two important conclusions follow from the discussion of the sensitivity factors: the design variables of a composite wing internal structure can be modified to reduce skin laminate stress concentration; and the relative significance of control design variables becomes comparable to composite structural variables as the control-induced strain approaches 1 percent.

GENERAL DISCUSSION

Smart composite structure concepts that (1) are configured through the adaptation of intraply hybrid composites for sensors/controls, (2) include respective evaluation by using the equivalence between the thermal and electrical strains, and (3) are combined with probabilistic composite structural analysis, provide a formal and convenient procedure to probabilistically assess their potential in specific structural applications. Because of the in-service control feature, smart composite structures will evolve as useful design concepts for cost-effective and early utilization of composites in advanced and traditional structural applications. The procedure described herein provides an efficient means to probabilistically quantify the range of uncertainties in the various structural responses that control the design.

Since the entire system's components can be configured simultaneously, various trades can be performed to obtain least-cost/maximum-benefit configurations. The probabilistic sensitivity factors can readily be used to select the minimum number of experiments required to certify the safe life of specific structural systems and, thereby, hasten their applications in man-rated structures. Implementation to a specific structure would require the participation of control specialists and probable combinations of the sensors/controls described in references 11 and 12.

Other major design parameters that were traded in the past for specific structures include the power required to provide the controls, and the power generator and its weight. The initial and operating costs (life cycle cost) of the entire system must be evaluated for a system with structural design parameters to assure an acceptable risk. This can be accomplished by structuring formal tailoring methods with multiple objective optimization features. The procedure described herein forms the probabilistic simulation of smart composite structural behavior, which is fundamental to any formal tailoring procedure for maximizing reliability and minimizing risk.

SUMMARY OF RESULTS

A formal procedure for the probabilistic assessment of smart composite structures uses these concepts: the adaptation of the intraply hybrid concept for sensors/controls, the equivalence between electrical and thermal strains, and probabilistic composite structural analysis. The important results from the application of this procedure to a smart composite wing are as follows:

1. The scatter range in the distortions (angle of attack and vertical displacements) are probabilistically quantified. This scatter is sensitive to control-induced strain, which can be adjusted as needed.

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2. Small holes (near the root, about 20 percent chord) have negligible effect on the scatter range of wing distortions.

3. The uncertainties in the range of the ply longitudinal stress in the control (+45°) ply increase as the control-induced strain increases.

4. The uncertainties in the longitudinal (0°) ply stress decrease with increasing control-induced strain in stress concentration regions. Stresses in other plies must be evaluated for specific cases.

5. Sensitivity factors indicate that the sensor/control, electric field design variables dominate the stresses in the control ply and become more dominant as the control-induced strain increases.

6. Sensitivity factors for the controlled ply indicate that composite laminate and configuration, and internal wing construction dominate the ply stresses in their ply.

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TABLE I.—ASSUMED STATISTICS OF
MATERIAL PROPERTIES AT
CONSTITUENT LEVEL FOR
SKIN AND FRAME

Property	Distribution	Mean	Coefficient of variation
E_{f11}, Mpsi	Normal	31.0	0.05
E_{f22}, Mpsi		2.0	
G_{f12}, Mpsi		2.0	
G_{f23}, Mpsi		1.0	
v_{f12}		.2	
v_{f23}		.25	
E_m, Mpsi		.5	
G_m, Mpsi		.185	
v_m		.35	

TABLE II.—ASSUMED STATISTICS OF
FABRICATION VARIABLES

Variable	Distribution	Mean	Coefficient of variation
fvr	Normal	0.60	0.05
vvr		.02	.05
θ_p, deg		.00	.90 (stdv)
t_p, in.		.015	.05

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TABLE III.—ASSUMED STATISTICS IN SENSOR/CONTROL DEVICE

Variable	Distribution	Mean	Coefficient of variation
Secondary composite system volume ratio	Normal	0.50	0.05
Sensor/control volume ratio		.60	
Sensor/control modulus, Mpsi		12.4	
Sensor/control strain coefficient, in./V		2.0×10^{-8}	
Electric field strength, V/in.		1.0×10^{6}	
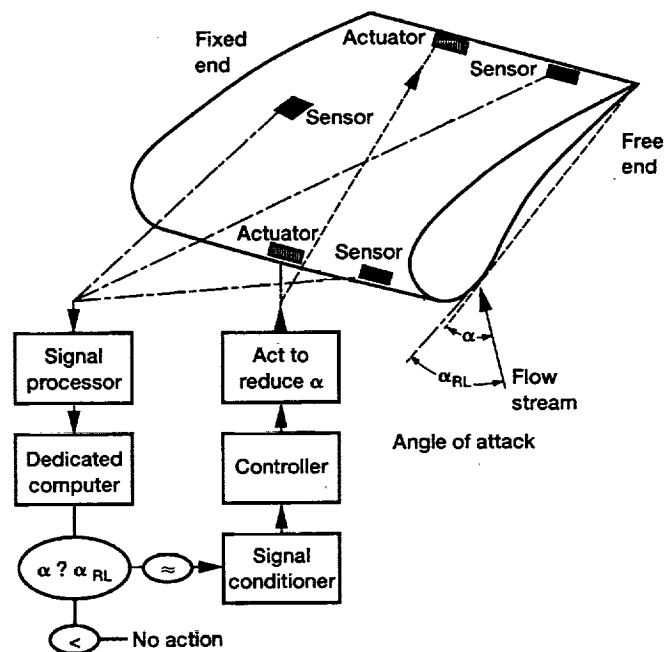
Figure 1.—Conceptual diagram of smart composite aircraft wing system.
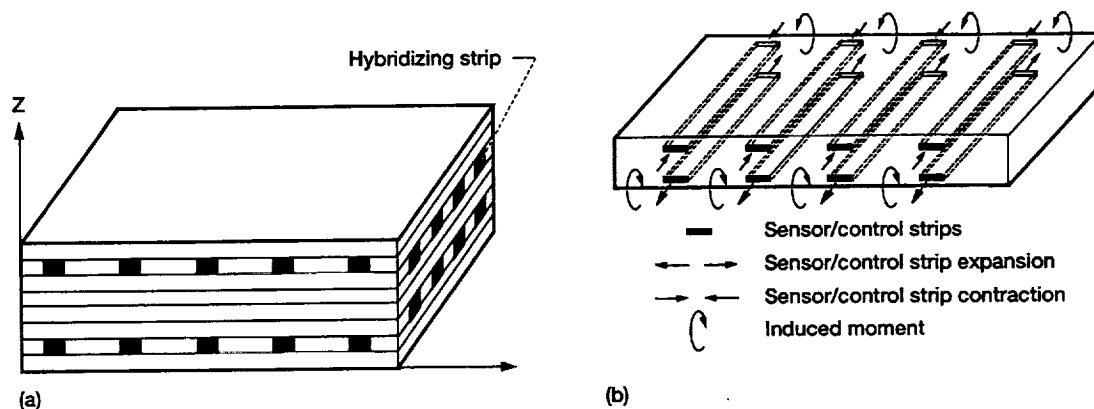
Figure 2.—Adaptation of intraply hybrid to smart composite system. (a) Intraply hybrid composite system. (b) Structural control using sensor/control materials.
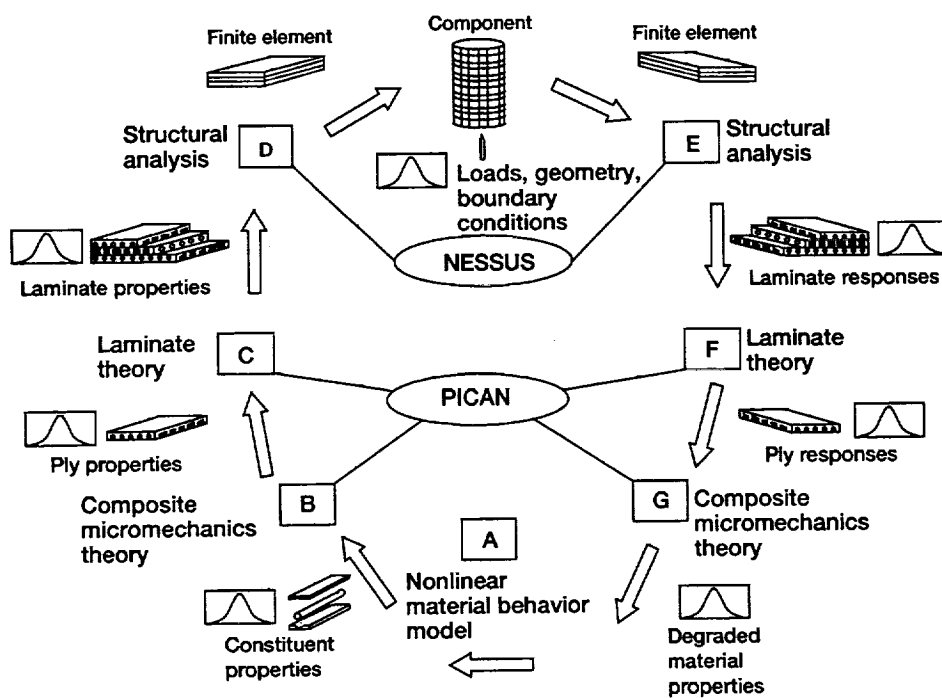
Figure 3.—Computer code IPACS.
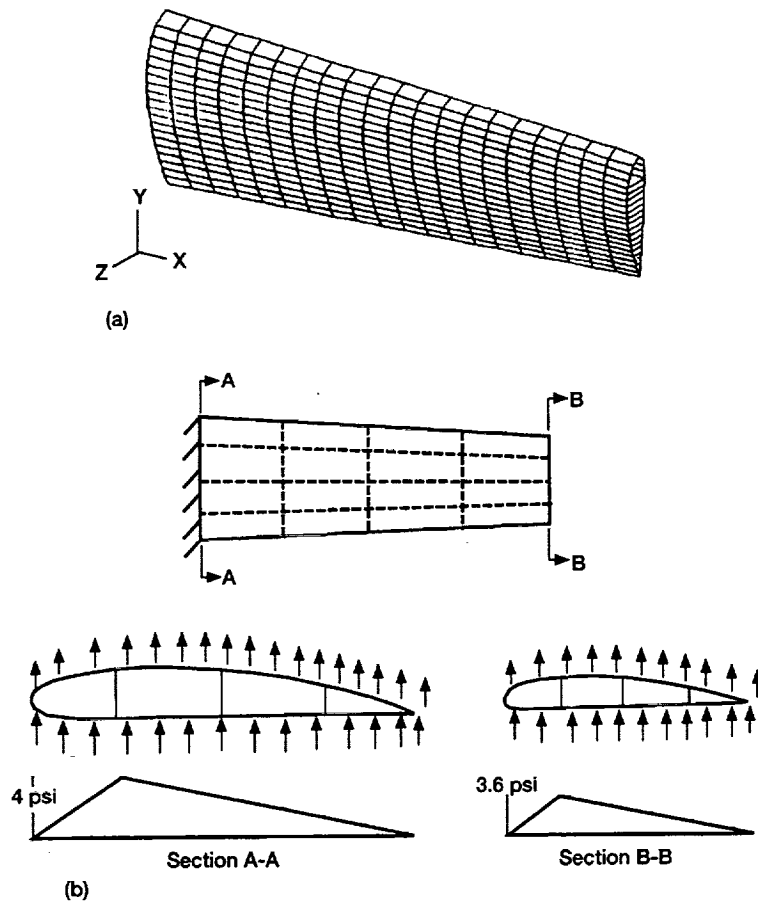
Figure 4.— Composite wing. (a) Geometry and finite element model of composite wing. (b) Mean pressure variation on composite wing.
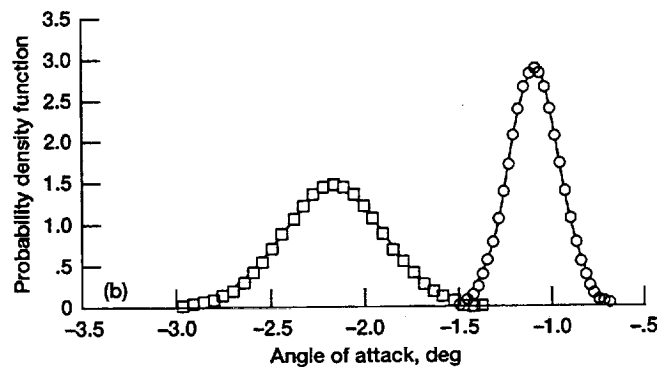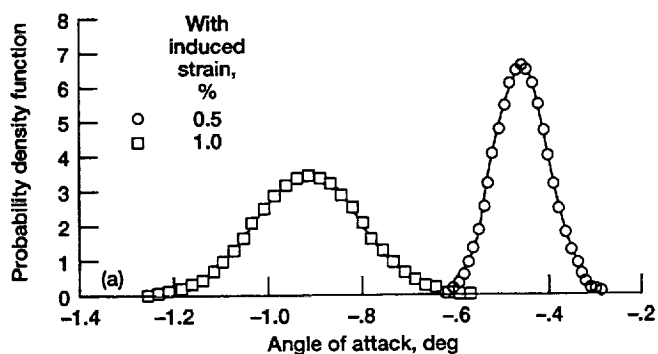
Figure 5.—Uncertainties range of angle of attack for smart composite wing without access openings. (a) At midspan. (b) At tip.
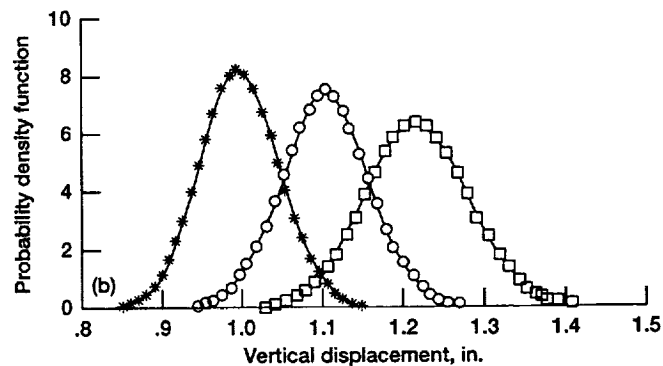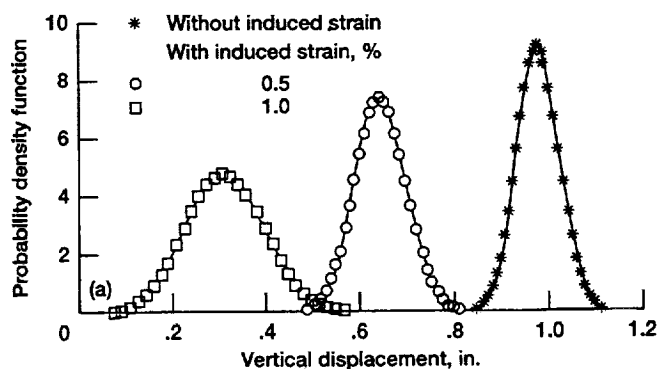
Figure 6.—Uncertainties range at midspan of vertical displacements for smart composite wing without access openings. (a) At leading edge. (b) At trailing edge.
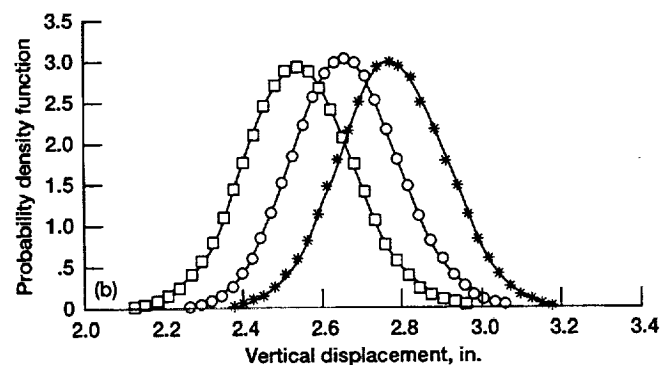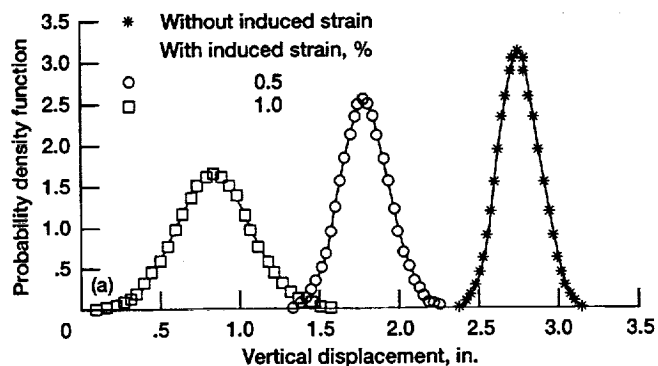
Figure 7.—Uncertainties range at tip of vertical displacements for smart composite wing without access openings. (a) At leading edge. (b) At trailing edge.
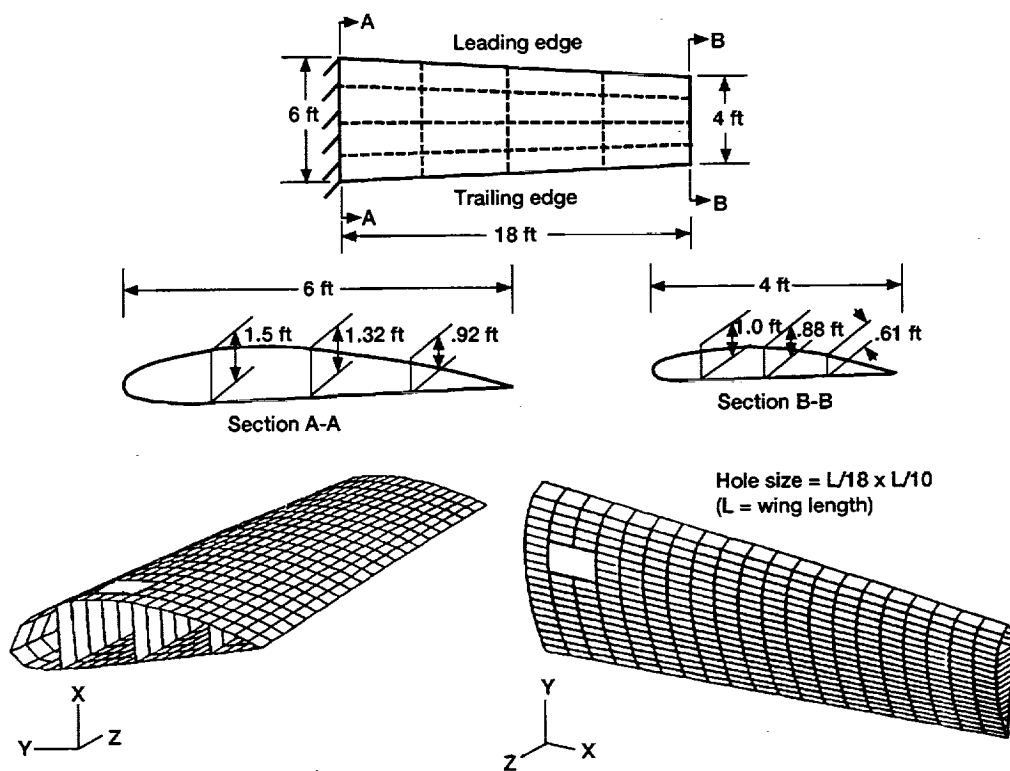
Figure 8.—Geometry and finite element model of composite wing.
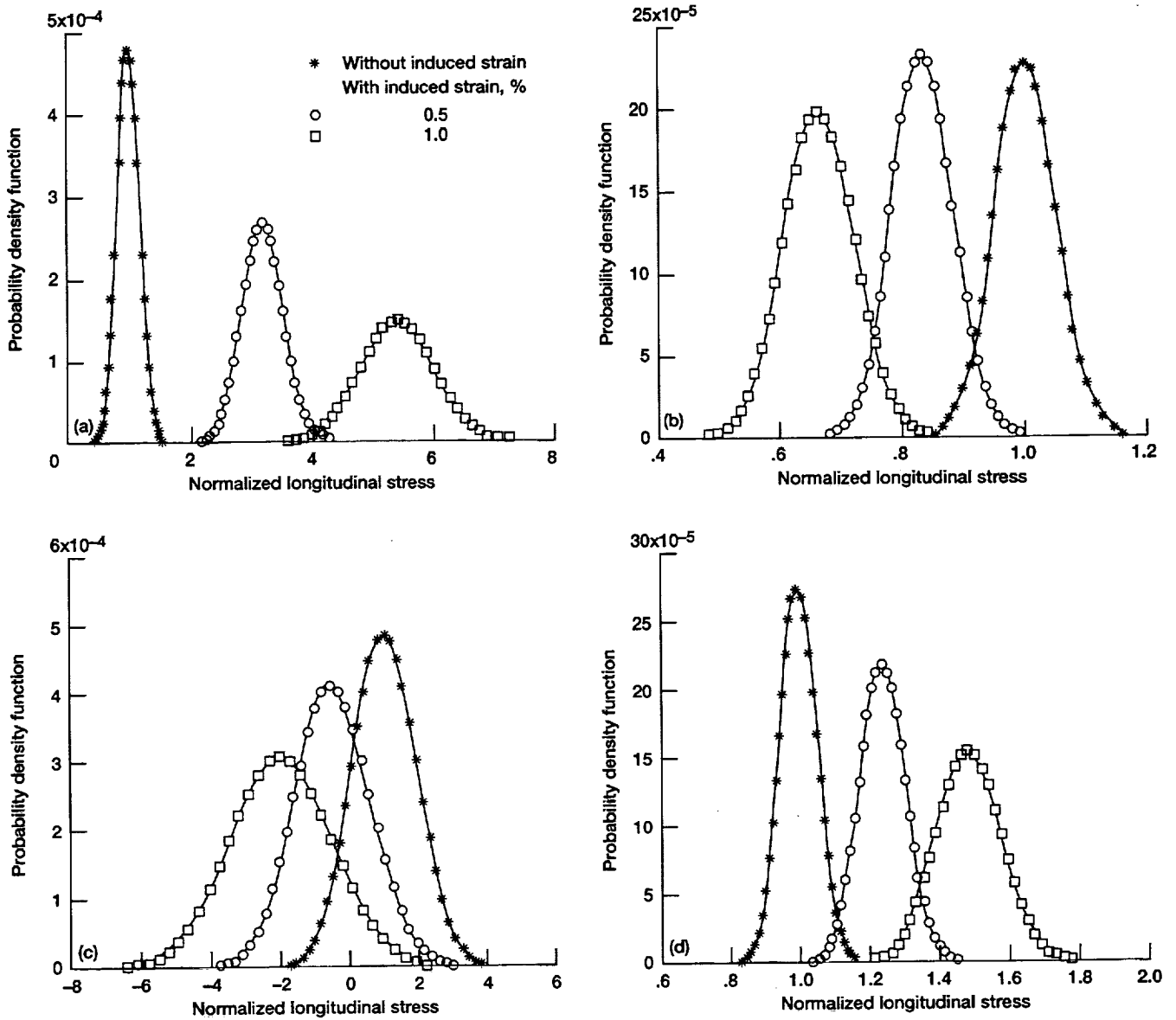
Figure 9.—Uncertainties range of normalized longitudinal stress with and without control for smart composite wing with small round hole. (a) 45° ply. (b) 0° ply. (c) –45° ply. (d) 90° ply.
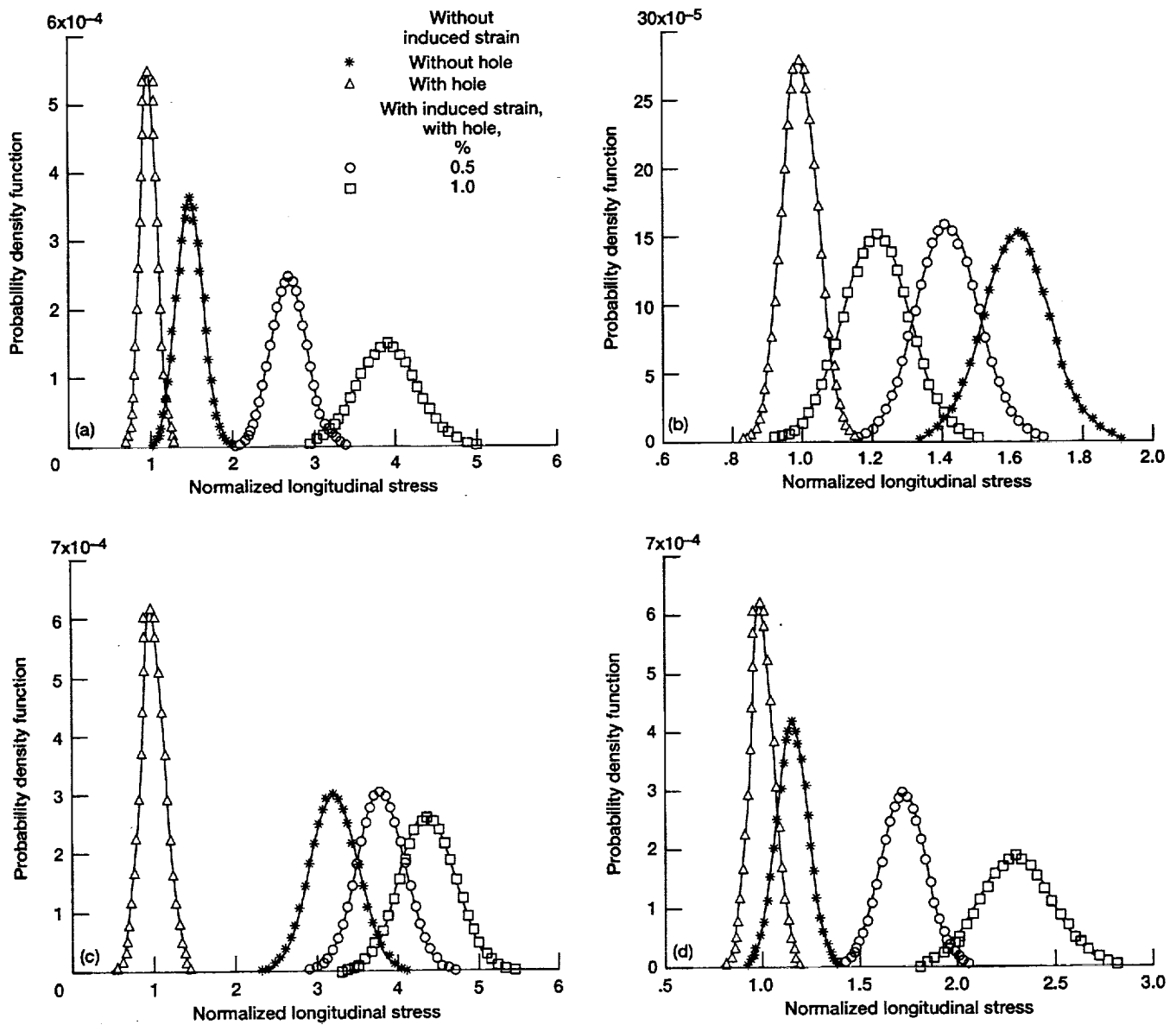
Figure 10.—Uncertainties range of normalized longitudinal stress with and without control for smart composite wing with and without rectangular opening. (a) 45° ply. (b) 0° ply. (c) –45° ply. (d) 90° ply.
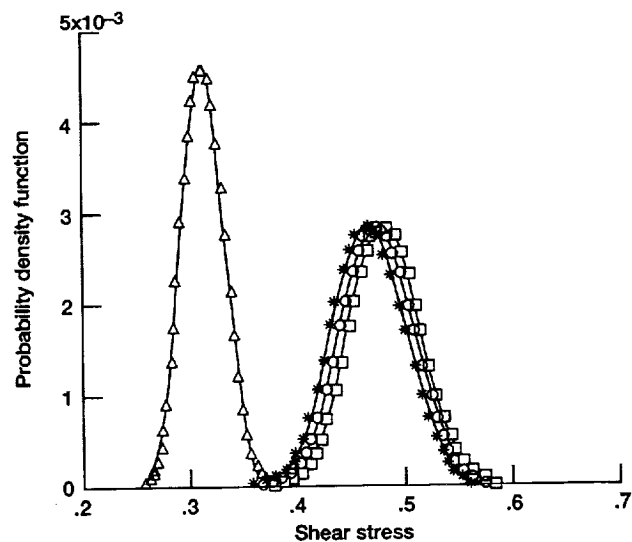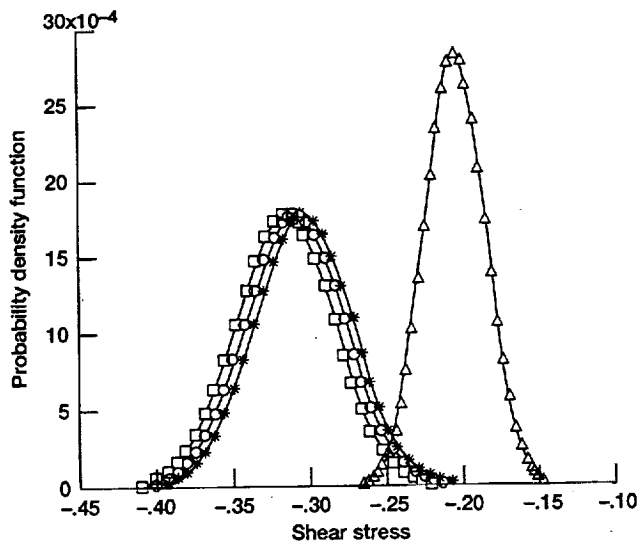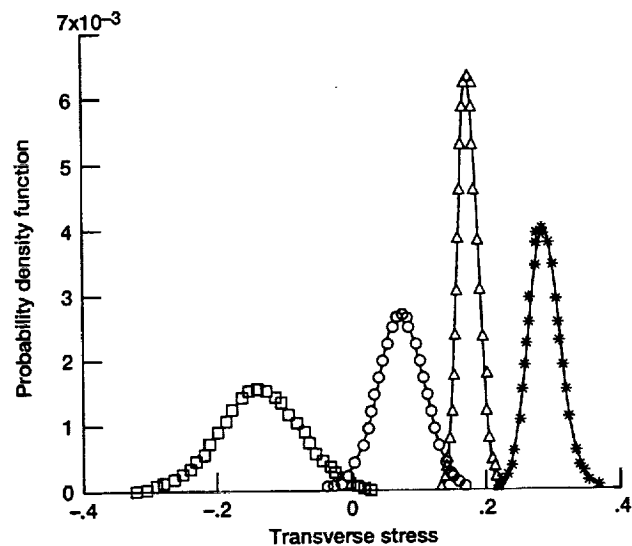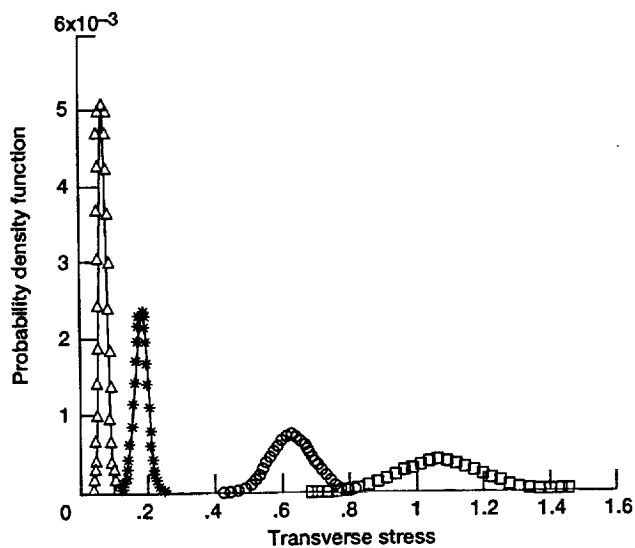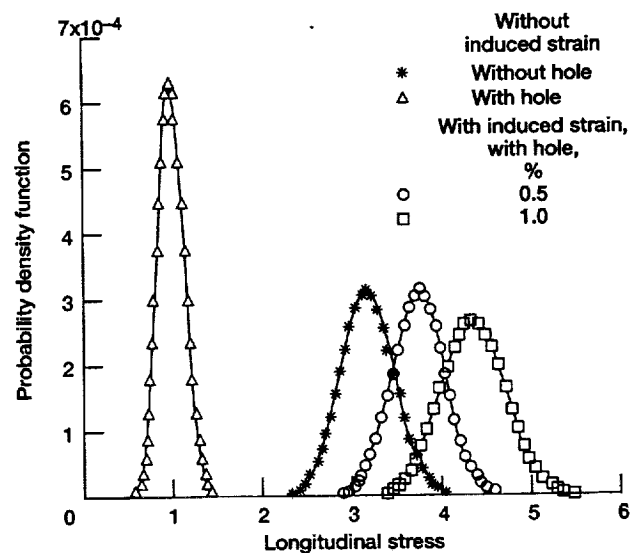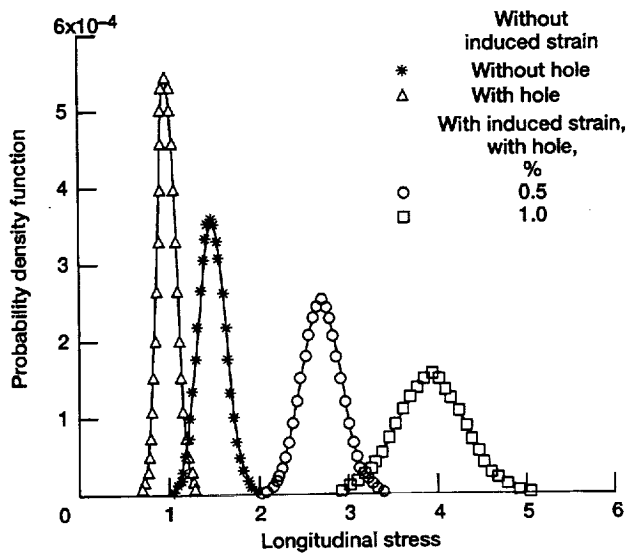
Figure 11.—Uncertainties range of normalized ply stresses in 45° ply for smart composite wing with rectangular cutout.

Figure 12.—Uncertainties range of normalized ply stresses in –45° ply for smart composite wing with rectangular cutout.
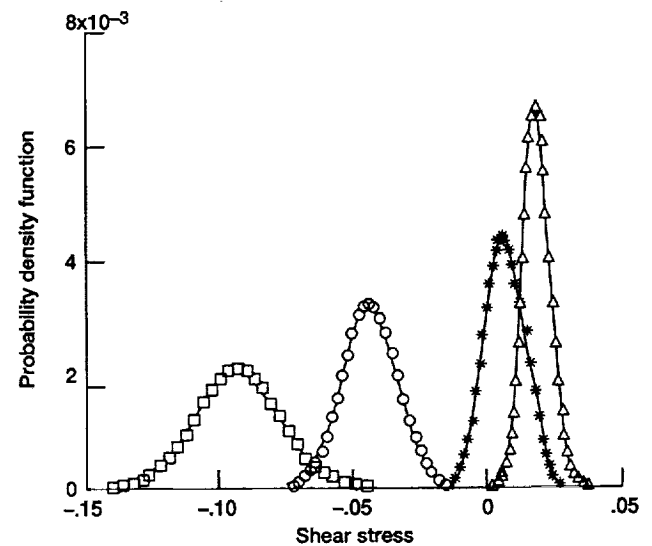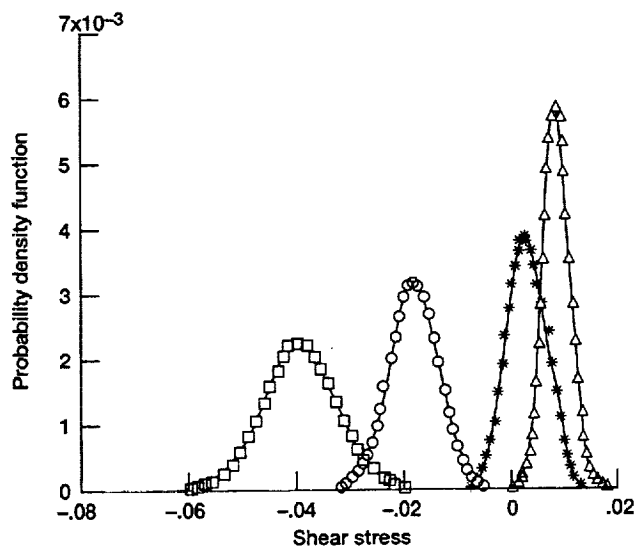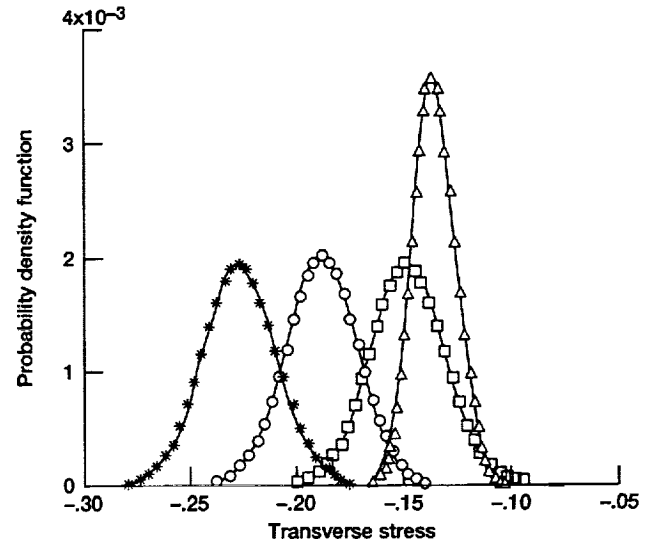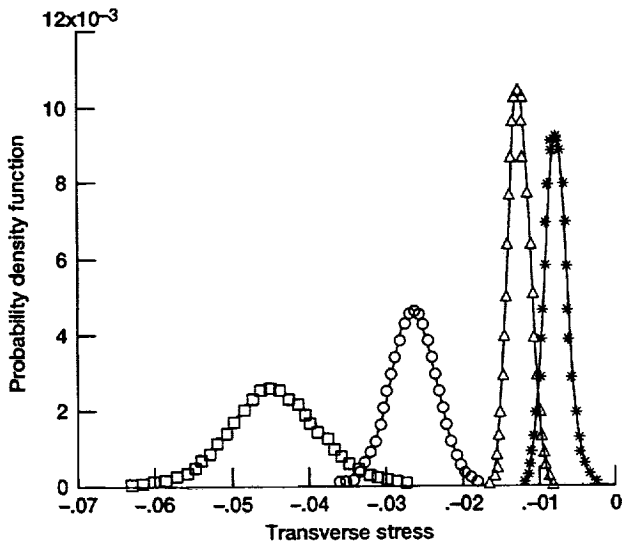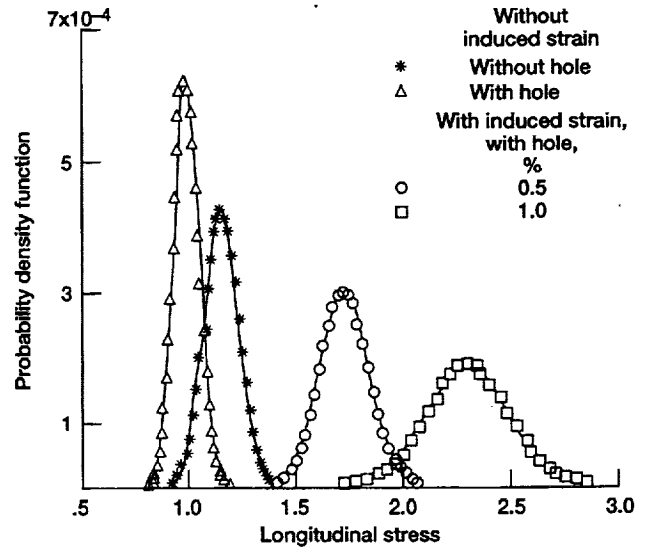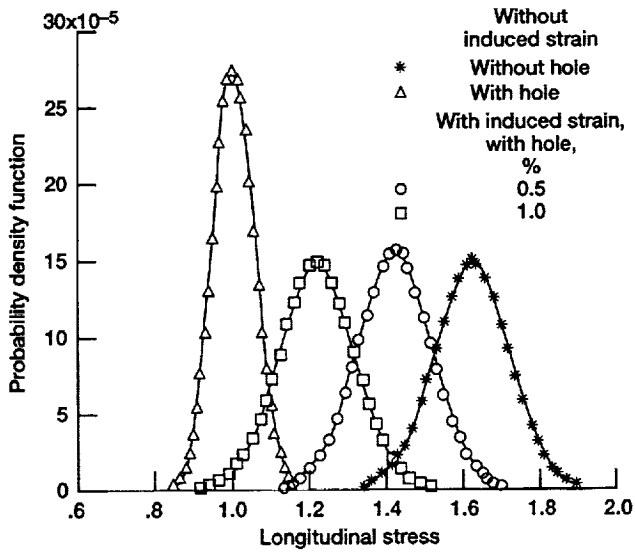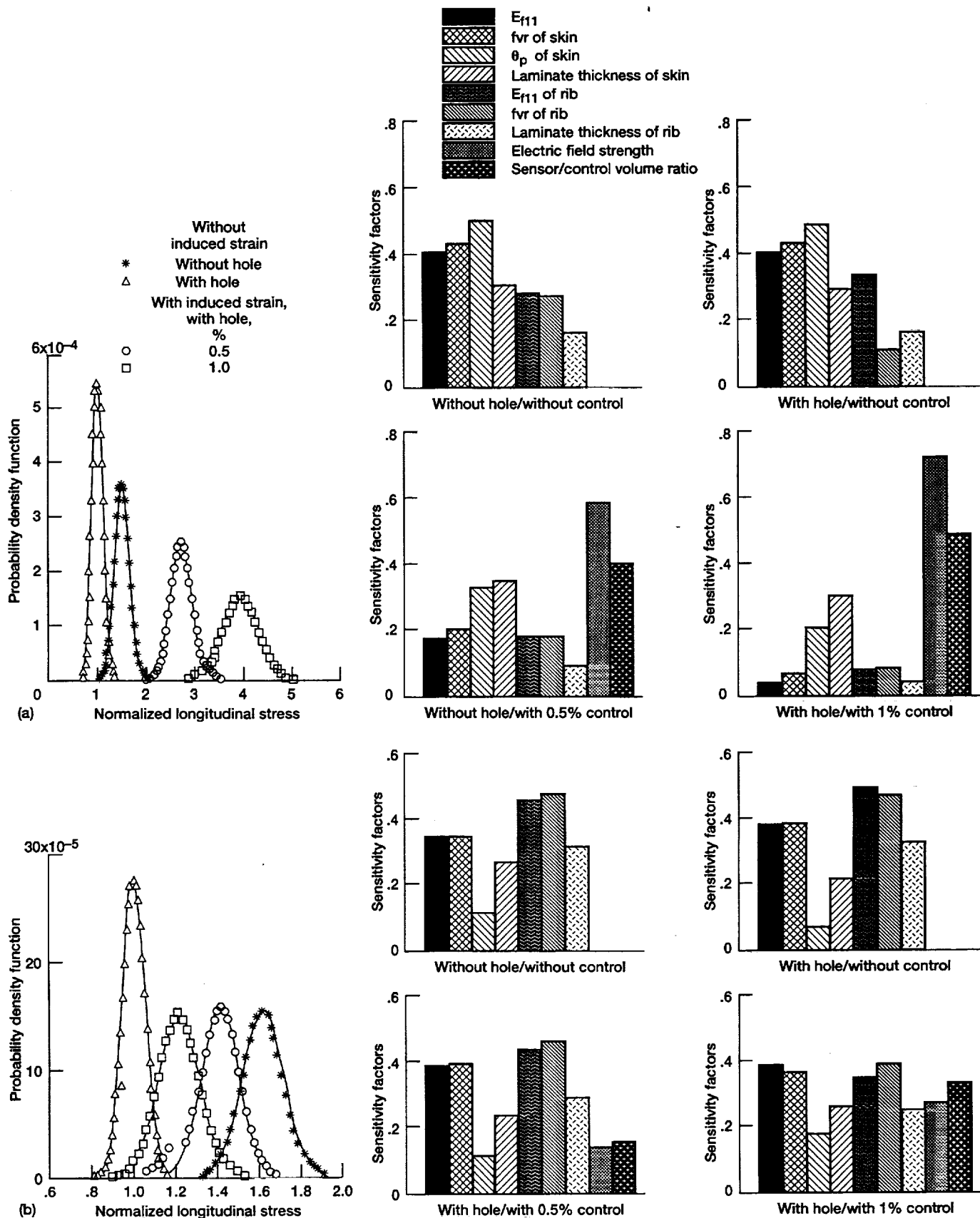
Figure 13.—Uncertainties range of normalized ply stresses in 0°
ply for smart composite wing with rectangular cutout.

Figure 14.—Uncertainties range of normalized ply stresses in 90°
ply for smart composite wing with rectangular cutout.

Figure 15.—Sensitivities for longitudinal stress in controlled plies for smart composite wing with rectangular cutout. (a) 45° ply. (b) 0° ply.

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13. ABSTRACT (Maximum 200 words)

A composite wing with spars and bulkheads is used to demonstrate the effectiveness of probabilistic assessment of smart composite structures to control uncertainties in distortions and stresses. Results show that a smart composite wing can be controlled to minimize distortions and to have specified stress levels in the presence of defects. Structural responses such as changes in angle of attack, vertical displacements, and stress in the control and controlled plies are probabilistically assessed to quantify their respective uncertainties. Sensitivity factors are evaluated to identify those parameters that have the greatest influence on a specific structural response. Results show that smart composite structures can be configured to control both distortions and ply stresses to satisfy specified design requirements.

14. SUBJECT TERMS

Adaptive; Intraply; Hybrid; Sensor; Control; Polarization; Uncertainty; Reliability; Fibers; Matrices; Ply stresses; Displacements defects; Sensitivities

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